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ELECTRODE MATERIALS FOR PROTONICALLY CONDUCTING SOLID ELECTROLYTE FUEL CELLS

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August 1983

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Project- ERP-4.5.5.0.53
Hydrogen-Air Fuel Cell

26 pf

ENERGY RESEARCH PROGRAM
MINERAL SCIENCES LABORATORIES
DIVISION REPORT ERP/MSL 83-120 (IR)

MICROMEDIA
JAN 20 1984

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by

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ABSTRACT

Concepts of ideal and real fuel cells are presented. These principles are applied to the formulation of the following material selection criteria: chemical stability, mechanical stability, electrochemical activity, and economic feasibility. Candidate electrode materials and deposition processes are also discussed.

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MATÉRIAUX D'ÉLECTRODE POUR DES PILES À COMBUSTIBLE DONT L'ÉLECTROLYTE SOLIDE EST CONDUCTEUR PROTONIQUE

par

J.D. Canaday*, A.K. Kuriakose*, A. Ahmad* et T.A. Wheat*

RÉSUMÉ

Les concepts de piles à combustible réelles et idéales sont décrits. Ces principes sont ensuite appliqués à la formulation des critères de sélection des matériaux qui suivent: stabilité chimique, stabilité mécanique, propriétés électrochimiques et faisabilité économique. Des matériaux qui pourraient servir d'électrode et des procédés de précipitation sont également examinés.

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INTRODUCTION

Fuel cells are well known for their ability to produce electric power and operate with efficiencies approximately twice those found for Carnot-cycle devices. These cells are also environmentally advantageous because their chemical byproduct contains only water when hydrogen is used as the fuel. They operate quietly and result in high energy densities. The industrial use of liquid electrolyte, molten carbonate, and solid electrolyte cells has been reviewed (1).

A portion of fuel cell development has been directed towards the generation of electrical energy from non-petroleum based fuels such as hydrogen obtained from the hydrolysis process. Following the 1973 energy shortage, the possibility of a shortage of technolgical materials has also been seen. It has been pointed out (2) that there is no shortage of potential energy sources, but rather that there is a lack of technology that will permit the optimum use of the abundance of energy available; this author has argued for the development of new energy systems based on improved materials properties.

The major technical problems associated with fuel cells are related directly to their component materials where the primary components are the electrolyte and the electrodes (anode and cathode). For example, component corrosion may result with low-temperature (100-200°C) fuel cells using phosphoric acid or potassium hydroxide liquid electrolytes. Circulation of the electrolyte by an external pump also reduces the overall system efficiency. At these low temperatures it is also necessary to have electrodes with a high level of catalytic activity using metals of the platinum group in order to produce fuel and oxidant dissociation and ionization. Fuel cells operating at high temperatures have also been constructed. The best known cell of this type utilizes the ZrO_2 solid electrolyte, which typically operates at 1000°C. However, this thermal environment results in chemically unstable conditions that reduce the lifetime of the cell components and cause deleterious effects on the cell performance. The solution to many of the problems associated with fuel cells may be found in the development of new solid state components.

Solid electrolytes are currently under development at CANMET as part of CANMET Project 4.5.5.0.53, the Hydrogen-Air Fuel Cell. The most promising of these are the protonically conducting β/β"-alumina and NASICONS (3-8).

The ionic conductivity of these electrolytes is in the range of 10^{-2} to 10^{-1} $(ohm\text{-}cm)^{-1}$, which is comparable to those found for solid electrolytes based on ZrO_2. The results of these research efforts indicate that the protonic electrolytes show good potential for use in fuel cells operating in the moderate temperature range of 250-300°C.

Literature searches have revealed no specific experimental results regarding electrode materials for protonic solid state electrolytes. The Proceedings of the Danish-French Workshop on Protonic Electrolytes suggested the rare earth intermetallic compound, $LaNi_5$, for the anode and the perovskite, $LaFeO_3$, for the cathode (9). These materials have the important properties of catalytic activity and, compared with Pt, low cost.

The objectives of this report are threefold. First, the basic principles of fuel cell thermonynamics and kinetics will be given. These principles will then be applied to the establishment of criteria for the selection of electrode materials. Thirdly, several candidate materials and deposition processes will be discussed.

FUEL CELL PRINCIPLES

THE IDEAL FUEL CELL

A fuel cell may be considered as an ideal system under equilibrium or reversible conditions. In practical terms this means that the cell is operated at open circuit. This configuration does not result in a useful device, but it is fundamentally important in establishing the concepts of thermodynamics, efficiency, and electromotive force. These principles have been discussed in detail (10,11), and the basic laws will be presented here.

Fuel cell efficiency, defined in the same way as that for Carnot systems, is the ratio of work output to energy input. The decrease in the Gibbs function, ΔG, is taken as the electrical energy obtained for a corresponding decrease in enthalpy, ΔH, of a particular chemical reaction. Thus, the ideal efficiency of a fuel cell is given by

$$\eta = \frac{\Delta G}{\Delta H} \tag{1}$$

or

$$\eta = \frac{nFV_e}{\Delta H} \tag{2}$$

where n is the number of electrons per mole, F is Faraday's constant, 96,485 Coulombs per mole, and V_e is the equilibrium voltage of the cell.

These thermodynamic data (10) are shown in Table 1 for the H_2/O_2 reaction. The ideal efficiencies for this reaction as a function of temperature are shown (10) together with the Carnot-cycle efficiencies in Figure 1. The ZrO_2 type fuel cell operating at 1000°C would have a thermodynamic efficiency of 72%. A protonic electrolyte fuel cell with an operating temperature of 300°C would have an ideal efficiency of 88%.

The open-circuit potential or electromotive force (emf) of a fuel cell or an individual electrode is defined in terms of a reversible electrode process:

$$xA + ne \rightleftharpoons yB \tag{3}$$

Table 1 - Thermodynamic efficiency of the H_2/O_2 fuel cell*

Reaction	Temperature °K	ΔH kJ·mol^{-1}	ΔG kJ·mol^{-1}	Efficiency %
$H_2O(g) + \frac{1}{2}O_2(g) \rightarrow H_2O(g)$	298	-241.7	-228.5	94.5
	500	-243.7	-219.0	89.9
	1000	-247.6	-192.5	77.7
	2000	-252.0	-135.1	53.6

*After (10)

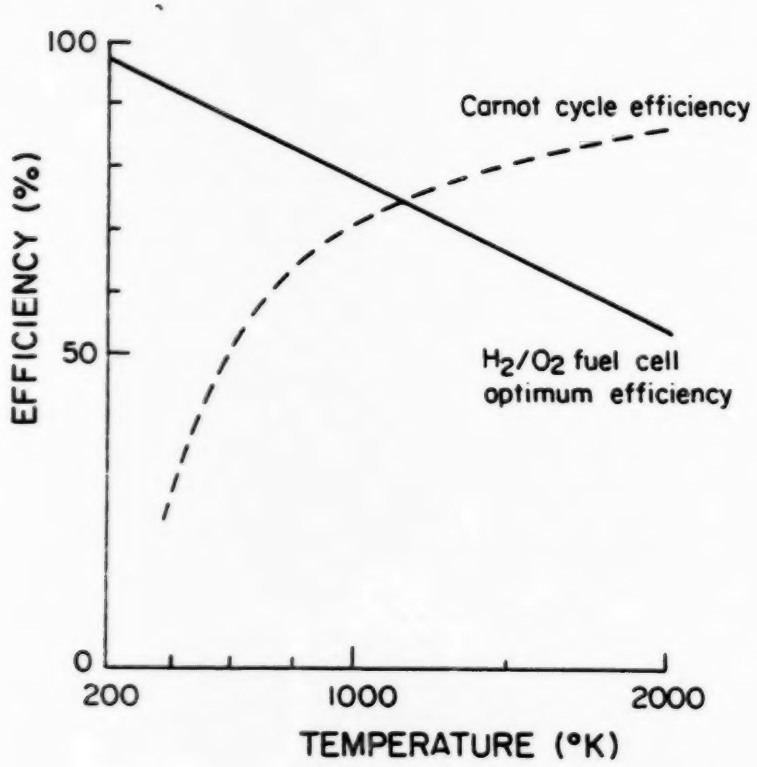

Figure 1 - Comparison of Carnot cycle efficiency and ideal efficiency of hydrogen/oxygen fuel cell.
(Ref. 10)

For a given concentration or pressure of A and B, the electrode will assume an equilibrium potential whose value is given by the Nernst equation:

$$V_e = V_o + \frac{RT}{nF} \ln \left(\frac{(a_A)^x}{(a_B)^y} \right) \qquad (4)$$

Here, R is the gas constant, T is the absolute temperature, and a_A and a_B are the activities (or pressure) of the reactants. The term, V_o, is the "standard potential" of the system (12) and is the value of V_e when both a_A and a_B have values of unity.

REAL FUEL CELLS

In order for a fuel cell to produce electricity from the combustion of fuel and oxidant, the net current has a non-zero value, and the cell operates under the closed circuit condition of non-equilibrium. In this case, the Nernst equation is no longer valid (13) and the Butler-Volmer concept is employed; this latter equation reduces to the Tafel relation at high overpotentials far from equilibrium or to a linear form at low overpotential near equilibrium.

A schematic view of a solid electrolyte fuel cell is shown in Figure 2. The dotted line represents a simplified view of the electrical current loop. This current consists of electron (or hole) flow in the electrodes and of ionic migration in the electrolyte. Within region 3, the electrolyte, conduction should be entirely ionic in order to prevent an electronic short circuit of the cell. In practice, the ratio of ionic conduction to electronic conduction is in excess of 10^3. For suitable electrode performance, regions 1 and 5, this ratio should be less than 10^{-3}. Within the electrodes there is also the mass transport of fuel and oxidant gases, which requires that the electrodes be porous. The external portion of the circuit is shown as region 6 where a load is placed or where the open circuit condition exists. At the interfaces, regions 2 and 4, fuel and oxidant gas molecules are dissociated and ionized usually with the aid of catalysts. In protonic conducting electrolytes, hydrogen species such as H_3O^+ or H^+ migrate from the anode to the cathode where the combustion product, H_2O, is formed.

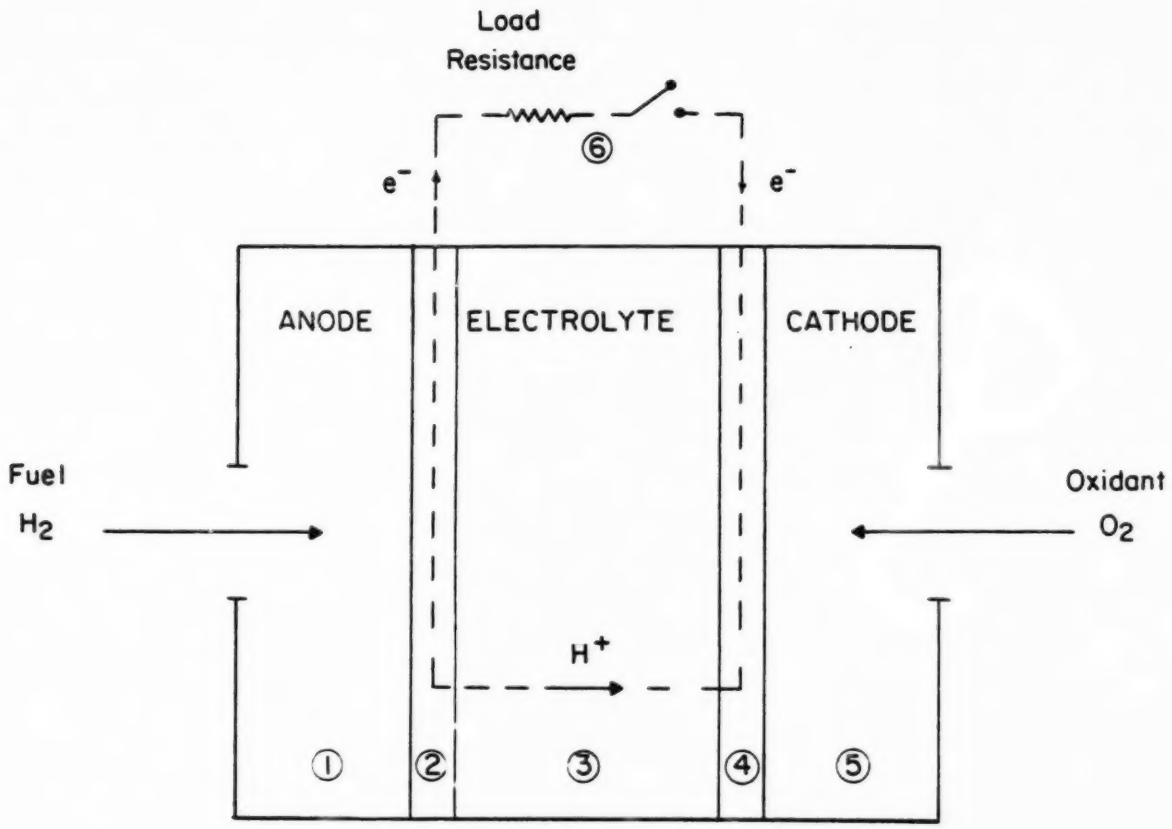

Figure 2 - Schematic diagram of protonically conducting hydrogen/oxygen fuel cell.

When the fuel cell produces electricity, the voltage difference between the anode and cathode, V_i, is less than what is measured under equilibrium (open-circuit) conditions, V_e. These voltages have corresponding power densities, W_i and W_e. This decrease in potential is caused by various overpotential processes that occur at the anode and cathode as well as within the electrolyte, V_a, V_c, and IR, so that the non-equilibrium potential is given (14) by:

$$V_i = V_e - (V_a + V_c + IR) \qquad (5)$$

The efficiency of the cell is correspondingly reduced to

$$\eta = \frac{n\,FV_i}{\Delta H} \qquad (6)$$

The type and magnitude of the overpotential depend on the amount of current drawn by the cell. Three basic types of overpotential have been identified as activation, ohmic, and concentration. The current-voltage relationship for the ohmic case is, of course, linear whereas for activation and concentration polarization, it will depend on the electrode processes involved. In many cases, it is possible to distinguish the various forms of polarization, and it is known that activation polarization is the dominant process at low current densities. Ohmic overvoltage occurs at medium current densities, and concentration overvoltage prevails at high current densities. A schematic comparison of the ideal and real fuel-cell current-voltage characteristics is shown in Figure 3. Also shown is the power density, W_i, which is obtained from the product of the cell voltage and the current density. It can be seen that the power density reaches a peak value before declining.

COMPARISON OF ZrO_2-TYPE AND β''-Al_2O_3-TYPE SOLID ELECTROLYTE FUEL CELLS

Table 2 gives a comparison of some of the properties of ZrO_2-type and Al_2O_3-type fuel cells. The previously discussed operating temperatures, theoretical efficiencies, and electrolyte conductivities are shown. The ionic transport numbers represent the fractions of the electrolyte ionic conductivity due to the migration of anionic (negatively charged) and

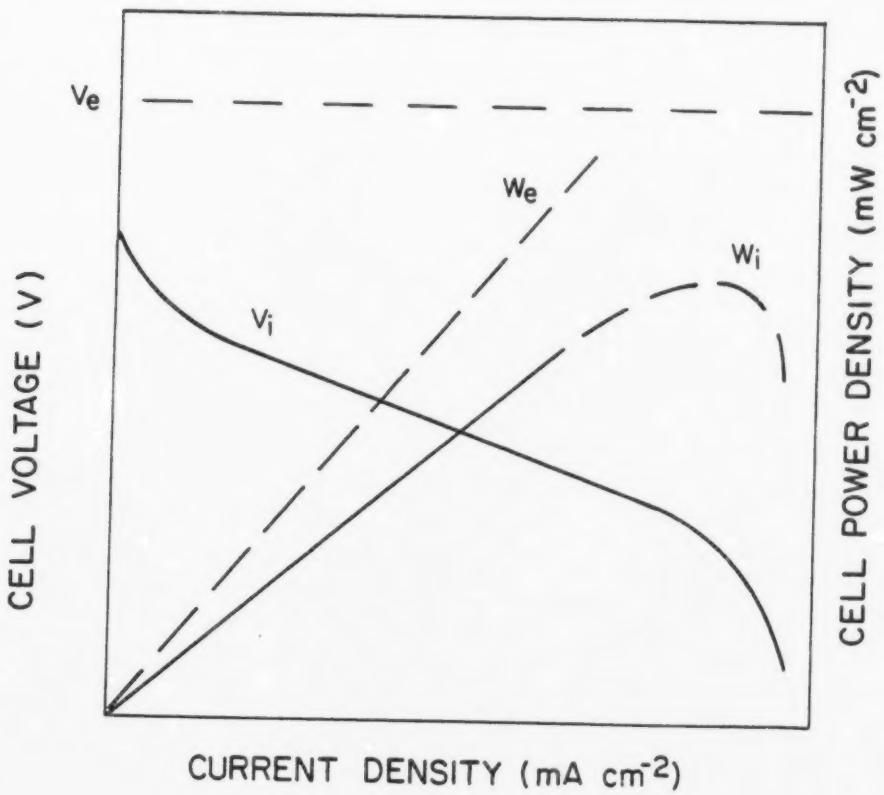

Figure 3 - Voltage-current and power-current relationships for the hydrogen/oxygen fuel cell. (Ref. 14)

Table 2 - Comparison of ZrO_2 and Al_2O_3 fuel cells

Property	ZrO_2-Type	β''-Al_2O_3-Type
Typical operating temperature	1000°C	300°C
Theoretical efficiency	72%	88%
Electrolyte conductivity $(ohm\text{-}cm)^{-1}$ at operating temperature	10^{-3} - 10^{-1}	10^{-3} - 10^{-2}
Ionic transport numbers		
Anionic	1.0	0.0
Cationic	0.0	1.0
Operating problems	Thermal environment Chemical reactivity of components	Unknown

cationic (positively charged) species. For the ZrO_2 electrolyte, ionic conductivity occurs primarily by the transport of O^{2-} ions from the cathode to the anode (15). The anionic and cationic transport numbers are very nearly unity and zero respectively. In contrast with this system, the protonically conducting electrolytes (16) have anionic and cationic transport numbers of zero and unity. The charge neutralization process:

$$2H^+ + O^{2-} \rightarrow H_2O \qquad (7)$$

will, therefore, occur at the anode for the ZrO_2 cell and at the cathode for the β''-Al_2O_3 cell as can be seen by referring to Figure 2. The operating problems of the ZrO_2 cell are related to its high temperature; those of the Al_2O_3 cell have yet to be defined.

ACTIVATION POLARIZATION MECHANISMS

Activation polarization (or overpotential) is related to both the chemical reactions and to the adsorption processes that occur at the electrode–electrolyte interface. The rates of these mechanisms can be increased by using electrode materials that have electrocatalytic properties. Because there is no completely satisfactory theory of the electrocatalytic process, researchers have been forced to rely on empirical relations for the selection of fuel cell electrode materials. The rate of electrochemical reactions has been correlated (11) with parameters such as work function, free energy of adsorption, and the number of d-electrons.

Hydrogen Electrode

The overall anode reaction resulting in the oxidation of hydrogen for acidic or protonically conducting electrolytes is:

$$H_2 \rightarrow 2H^+ + 2e^- \qquad (8)$$

This reaction consists of numerous intermediate steps involving absorption, molecular dissociation, atomic ionization, and surface migration. The reaction may also include processes associated with concentration polarization, such as gas diffusion. The slowest process, that is the rate-determining step, depends on the electrode composition. For example, platinum anodes are found (11) to be limited by the diffusion of hydrogen to the electrode. On nickel anodes it was found that the dissociation step limited the rate of the entire process.

Oxygen Electrode

At the cathode, the overall reaction is:

$$\tfrac{1}{2}O_2 + 2e^- \rightarrow O^{2-} \qquad (9)$$

Electrolyte polarization has been investigated (17) for the CeO_2 cell. Data were found to fit the Butler–Volmer equation, implying a charge-transfer (or activation) mechanism. Contradictory results (18) were attributed in part to electrode morphology. The kinetics of the ZrO_2–Pt interface have also been studied (19), and the polarization mechanism was explained by a charge transfer process.

Ohmic Polarization

Resistance of either the electrolyte or the electrode will limit the flow of electronic current to the external circuit and will thus linearly reduce the cell voltage as a function of current density. Electrolyte conductivity is determined from Arrhenius plots, and values of 10^{-2}-10^{-1} $(ohm\text{-}cm)^{-1}$ can be obtained for protonic electrolytes. The resistivity of the electrode is usually negligible, but substantial values may result with porous oxide cathodes.

Concentration Polarization

The concept of concentration polarization when applied to liquid-electrolyte fuel cells refers to the depletion of ionic species in the electrolyte and near the electrode-electrolyte interface. The width of this depletion region is of the order of 0.01 cm (20). For solid electrolytes, the depletion region will be only a few atomic layers in thickness (21), and concentration polarization will result when there is a deficiency of fuel or oxidant gas at the interface. In order for these gases to reach the interface it is necessary that the electrode be porous. It will also be necessary to characterize the morphology of the electrodes. Measureable parameters of the electrode structure will include its thickness, porosity, particle size distribution, and surface area. It has been found (22) that the diffusion of oxygen gas in the pores of the Pt cathode limits the obtainable current of the ZrO_2 cell.

SELECTION CRITERIA FOR ELECTRODE MATERIALS

The criteria applied in selecting electrodes have been discussed for the ZrO_2 cell (23), the protonic cell (24), and for ZrO_2 oxygen sensors (25). The primary areas of consideration are: a) chemical stability, b) mechanical stability, c) electrochemical activity, and d) economic feasibility. High temperature cells will favor fast catalytic steps at the expense of a severe thermal atmosphere. Low or moderate temperature cells, on the other hand, will require electrodes with good electrocatalytic activity under less severe thermal conditions. These four criteria can be generally applied to any fuel cell system, but the relative importance of

each will depend on the specific system.

Thermodynamic stability and component lifetimes of several years are the primary considerations regarding chemical criteria. These requirements include:

1. Chemical stability of the cathode against oxidation and nitrification with air as the oxidant;

2. Chemical stability of the anode against hydridization with hydrogen as the fuel;

3. Minimal reactivity of the electrodes with the electrolyte and connecting materials;

4. Low vapour pressure to minimize electrode volatilization loss;

5. Phase stability of the electrodes with no allotropic transformations over the operating temperature range.

The electrodes must have mechanical properties that will ensure that the electrochemical functions of gas transport and catalysis functions will be maintained during fuel cell operation. Thus, the optimized electrode structure required for gas transport and electrocatalysis should remain unchanged.

Physical and electronic contact between the electrode and the electrolyte requires that the differential thermal expansion of these components be minimized. Although the operating temperature of the protonic fuel cell will be approximately 300°C, the firing temperature for the electrode after deposition on the solid electrolyte is ≈1000°C. Therefore, the differential rates of thermal expansion between the electrolyte and the electrode must be minimal. If the electrode is metallic, stress relief by plastic flow can occur. Oxide electrolytes, on the other hand, will not flow elastically, and cracking or spalling may cause loss of adhesion between the electrode and the electrolyte. The chemical bond strength between these components will be an important property.

The electrochemical criteria of electrode materials reflect the need to minimize polarization loss and can be summarized as follows:

1. Minimize activation polarization by choosing materials with electrocatalytic properties for fast dissociation, ionization, adsorption, and surface migration steps.

2. Minimize ohmic polarization with electrolytes having high ionic conductivity and electrodes with high electronic conductivity.

3. Minimize concentration polarization with porous electrodes. The gas flow system should have a high flow rate and turbulent flow to reduce concentration gradients.

For protonic solid-electrolyte fuel cells to become economically feasible, materials and fabrication costs must be competitive with those of other power systems. The lower operating temperature of this cell (300°C) compared with the temperature of the ZrO_2-type cell (1000°C) means that the electrocatalytic performance of the protonic cell will be more important than for the higher temperature cell. Even with this restriction, it will be necessary to replace platinum electrodes with less expensive materials. Fabrication methods that reduce the fuel cell cost must also be considered. It should also be emphasized that economies resulting from longer component lifetimes can be obtained from materials with a high degree of chemical stability.

CANDIDATE MATERIALS

ANODE MATERIALS

Platinum is well known for its electrocatalytic activity and has been used extensively for electrodes with the ZrO_2 type fuel cell (18,19,26,27) The catalysis process will be even more important in the case of β''-Al_2O_3-type cells than for the ZrO_2 electrolyte because of its lower operating temperature. Therefore, this noble metal should be utilized at the anode during the initial stage of protonic cell electrode development program. For use with ZrO_2 fuel cells, platinum has been deposited on the electrolyte surface in the form of paste or by sputtering. Combined heat

and current treatments have been employed (28,29) to produce the porous structure required for gas flow.

Experiments (30) were conducted with Pt and Au anodes, which are known to have quite different electrocatalytic activities. The similarity of the polarization measurement obtained with these two metals indicated that most of the catalysis process occurred on the surface of the ZrO_2 electrolyte rather than on the anode. Similar experiments with protonic electrolytes would be useful in determining the relative catalytic roles of the anode and the electrolyte.

It has been suggested (9) that non-noble metals may provide sufficient reaction rates at temperatures near 200°C. Nickel is an obvious choice for the anode although it should not be considered as cathode material because of the formation of NiO or NiO_2 which are electronically insulating. Nickel can be deposited on solid electrolytes using the chemical vapour deposition method. Thin films of Ni are commonly produced by sputtering.

The rare-earth intermetallic compound, $LaNi_5$, was also discussed (9) for use as a hydrogen electrode in a protonic conducting fuel cell. This compound has high electrocatalytic activity and has shown long-term stability when used in an alkaline electrolyte nickel/hydrogen battery.

CATHODE MATERIALS

The majority of the research conducted on electrodes for the ZrO_2 cell has been concerned with cathode development, and most of the cathode studies have involved platinum. The lower operating temperature of the protonic electrolyte fuel cell will necessitate cathode materials with high catalytic activity. Platinum, therefore, should be the first metal tested at the cathode.

As a replacement for Pt, several electronically conducting oxides have been investigated as cathodes for the ZrO_2 electrolyte. The most successful group of oxides found to date is the perovskite type. It has been found (31) that the charge transport mechanism of lanthanum chromite is almost entirely electronic up to 1250°K with less than 0.05% being due to the transport of ions.

The electronic conductivities of the perovskites $LaCoO_3$ and $La_{0.9}Sr_{0.1}CoO_3$ at 300°C were measured (23) to be approximately 500 $(ohm\text{-}cm)^{-1}$. It was found (32) that strontium doping of the oxide, $La_{0.84}Sr_{0.16}CrO_3$, improved the sintering properties, reduced the

volatility, and increased the conductivity of this perovskite. It was also shown that Sr or Ni doping of $LaCoO_3$ resulted in conductivities in excess of 100 $(ohm\text{-}cm)^{-1}$. Furthermore, the composition, $La_{0.8}Sr_{0.2}CoO_3$, was found to have a polarization curve for oxygen reduction in 5 N KOH at 25°C similar to that of a Pt electrode. Measurement (33) of the dc and ac conductivities of $La_{1-x}Sr_xCrO_3$, $0 \leq x \leq 0.4$, was shown to have a thermally activated temperature dependence in the range of 300-1900°K. These measurements (34) also resulted in activation energies of 0.11-0.19 eV. The chemical stability of $LaMO_3$, (M = V, Cr, Mn, Fe, Co and Ni), was measured thermogravimetrically (35) at 1000°C in various gas mixtures. Electronic conductivities of these perevskites at 300°C were found to be in the range of 0.02 to 200 $(ohm\text{-}cm)^{-1}$. $La_{0.8}Sr_{0.2}CrO_3$ was suggested (25) as an alternative to Pt for high temperature oxygen sensors.

It should be emphasized that these perovskite studies were concerned with the bulk properties of the material. When used as cathodes for solid electrolyte fuel cells, porosity will be required for electrocatalysis and gas transport. Thus, the properties of porous cathodes will not be the same as those found for the bulk material. However, these results indicate that perovskites exhibit many excellent properties and should be considered as primary candidates for the replacement of Pt as the cathode material.

Three phases of electrode development can be conveniently defined in which platinum electrodes will serve as standards against which other materials may be compared. These materials and their deposition methods are shown in Table 3.

Table 4 gives a comparison of material costs (36-39) for electrodes. The nitrate, oxide and carbonate materials cost data are based on laboratory quantities; production-level amounts will be available at lower costs. These values also exclude the manufacturing costs of producing the electrodes either at the research stage or in production quantities and will vary with market conditions. However, it is clear from these data that the cost of electrode materials can be reduced by factors in the range of 20 to 1000 if the metals of the platinum group are replaced by less expensive metals or oxides. Also shown for comparison are the cost of electrolyte materials.

Table 3 - Candidate electrode materials

Electrode Development Phase	Anode		Cathode	
	Material	Deposition Method	Material	Deposition Method
1	Pt or Au	Paste or sputtering	Pt or Au	Paste or sputtering
2	Ni	Chemical vapour deposition or sputtering	Undoped $LaCoO_3$ or similar perovskite	Slurry or sputtering
3	$LaNi_5$	Sputtering	Doped $LaCoO_3$ or similar perovskite	Slurry or sputtering

Table 4 - Cost of electrode and electrolyte materials

Material	Cost $U.S.-g^{-1}$
Platinum Group Metals	
Rh	26
Pt	10
Ir	10
Pd	6
Ru	4
Os	4
Noble Metals	
Au	12
Ag	0.60
Iron Group Metals	
Co	0.02
Cr	0.01
Ni	0.01
Fe	0.01
Rare Earth Elements	
Y	0.36
La	0.07
Ce	0.06
Rare Earth Oxides	
Y_2O_3	0.09
La_2O_3	0.02
CaO_2	0.02
Perovskites Prepared from Nitrates	
$La_{1-x}\ Ca_x\ Co\ O_3$, x=0.3	0.23
$La_{1-x}\ Sr_x\ Co\ O_3$, x=0.1	0.22
Electrolyte Oxides and Carbonates	
MgO	0.07
ZrO_2	0.06
K_2CO_3	0.05
Al_2O_3	0.01
$NaHCO_3$	0.01

SUMMARY AND CONCLUSIONS

The development of electrodes for protonically conducting solid-electrolyte fuel cells should be based on materials that are chemically and mechanically stable at the operating temperature of ~300°C. These materials must also be electrocatalytically active at this temperature.

The disciplines of materials science, catalysis, electrochemistry, and surface science will provide new knowledge regarding the fundamental properties and process involved in these components. Technological developments in the areas of solid-state planar devices, thin films and sputtering will make controlled deposition possible, leading to components with reproducible properties. The chemical and mechanical stability requirements of electrode materials for protonic solid electrolyes operating at 300°C will be more easily met than for the ZrO_2-type fuel cell operating at 1000°C. Vapour pressure, heat of formation, and thermal expansion data of candidate electrode materials are currently being compiled for presentation in a subsequent report.

At the operating temperature of the protonic electrolyte fuel cell it will be necessary to have higher rates of electrocatalytic activity than those required for the ZrO_2 cell. Bulk diffusion of fuel and oxidant gases is approximately two to three orders of magnitude less at 300°C than at 1000°C, which means that the electrodes must have a high degree of porosity in order to minimize concentration polarization.

Electrode costs can be reduced in several ways. Materials costs will be decreased by replacing Pt electrodes with metals or oxides having comparable electrochemical activity. The use of thin-film technology will reduce the required amount of electrode material. Manufacturing costs can be lowered by employing large-scale deposition methods. The use of electrode materials that are chemically and mechanically stable will result in longer component lifetimes and hence in lower operating costs.

All deposition processes must result in porous structures or must allow for the production of porosity by heat and electrical treatments. The morphology of the anode and the cathode will involve a critical set of parameters that must be well defined and reproducible. The structure of the electrodes will significantly affect the three types of polarization mechanisms. Kinetic-catalytic and diffusion-morphology measurements will determine the rate-limiting process. Current density limits will probably

be most strongly affected by the cathode processes, followed in importance by those of the electrolyte and the anode.

Platinum, because of its well-known electrocatalytic properties and because of its common use as ZrO_2 fuel cell electrodes, should be utilized at both the anode and the cathode during the initial phase of the electrode development program. More abundant and less costly metals and oxides should then be used as electrode materials in subsequent stages. Results of polarization measurements for these materials can be compared with those obtained for platinum.

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